Setting the Standard for Automation™

Hot Section Physical Sensors and Instrumentation

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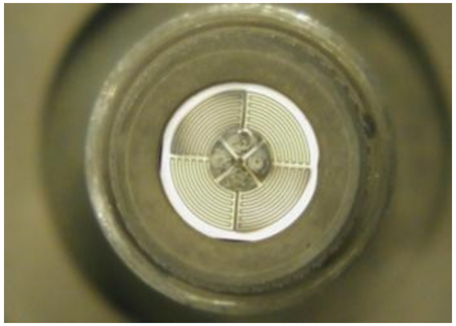
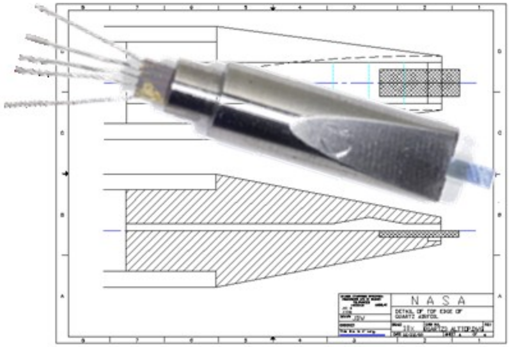
Presenter:
Gustave C. Fralick

- B. S. in Engineering Physics from UIUC, 1965
- M. S. in Physics, John Carroll, 1969
- Active in developing state-of-the art sensor technologies for aeronautics and space applications
- Over thirty papers published in the area of measurement of gas and surface temperature, heat flux, flow and strain in harsh environments.
- Has developed sensors such as the dual and multi-wire thermocouple, single and dual layer thin film heat flux gauges, drag force anemometer, high gas temperature probe and multifunction sensor.
- Current interests include using ceramic materials in high temperature sensors and in energy harvesting applications



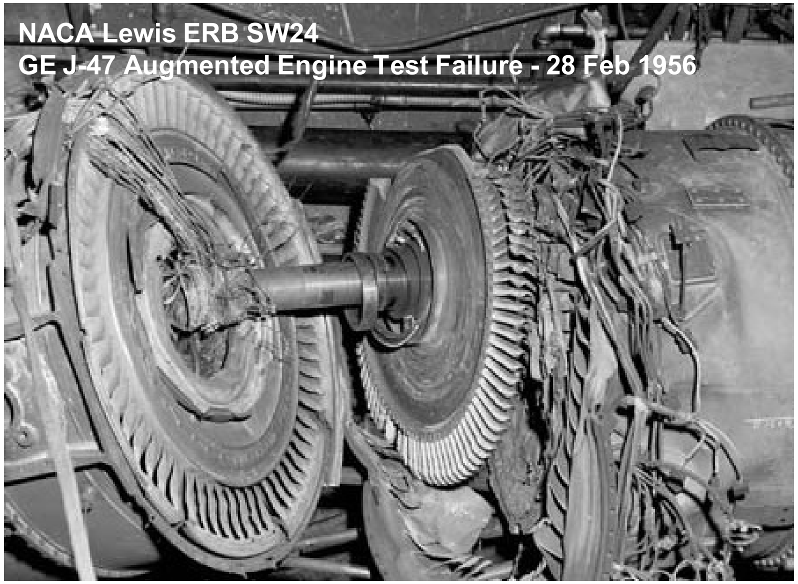


Physical Issues for Life Prediction of Engine Hot Section

- Centrifugal Stress
- Thermal Stress
- Vibrational Stress from gas flow
- Contact Stresses from different materials (Thermal Expansions, Deformations)
- Blade Clearance (Creep)

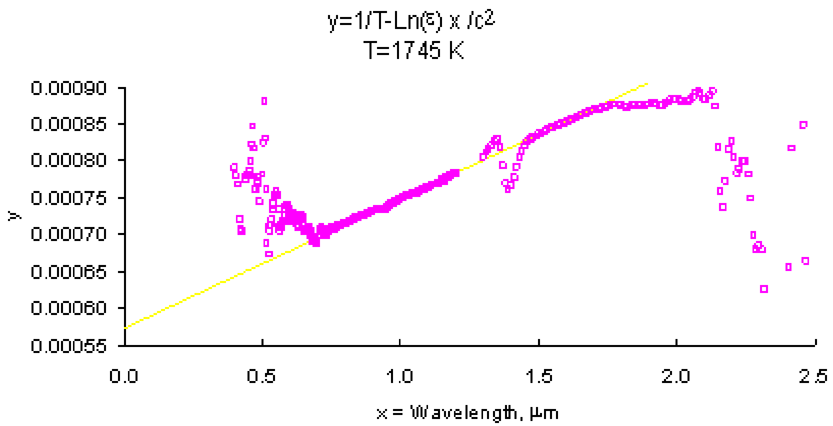
Malaysia Airlines Boeing 777-2H6ER
RR Trent 892 Blade Delamination - 03 Nov 2006

Air New Zealand Boeing 767-219ER
GE CF6-80A In-Flight Failure - 08 Dec 2002



NACA Lewis ERB SW24
GE J-47 Augmented Engine Test Failure - 28 Feb 1956

High Temperature Gas Temperature Probe



Tested at an atmospheric combustor to 1745K (1470C)

- Usable up to 2000°C in oxidizing atmospheres
- High gas temperatures correlated with NOx formation.
- Beryllia sheath - excellent resistance to thermal shock
- No water cooling needed- length: 0.28 m, diameter of the support section: 12.7 mm, the sheath diameter: 8 mm
- Signal transmitted from the probe to a multiwavelength pyrometer spectrometer via optical fiber- no EMI interference and no emissivity values needed.

High Temperature Gas Temperature Probe

MULTIWAVELENGTH PYROMETER TEMPERATURE MEASUREMENT

- It is a non-contact, non-intrusive method.
- Does not need emissivity or transmissivity information a-priori.
- Particularly useful for measuring surface temperatures of ceramics because of their low and complex emissivities.
- Uses spectral region 0.5 to 2.5 μm, 1.3 to 4.5 μm, or 2 to 14.5 μm depending on the requirement.
- Uses Plank's law appropriate for wavelength region, spectrometer, and special algorithm to provide both temperature and emissivity.
- Adapted here for use as part of high gas temperature measurement system.

High Temperature Gas Temperature Probe

- Planck's Law of Black Body Radiation:

$$L_\lambda = \varepsilon_\lambda \tau_\lambda \frac{c_1}{\lambda^5} \frac{1}{\exp\left(c_2/\lambda T\right)-1}$$

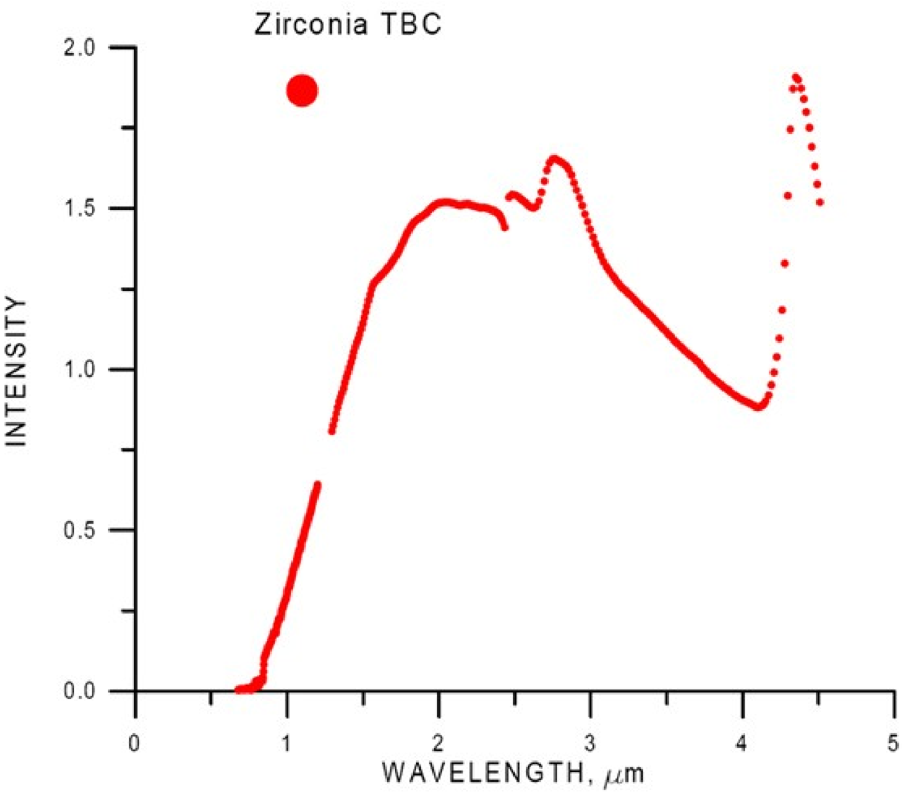
$$= \varepsilon_\lambda \tau_\lambda \frac{c_1}{\lambda^5} \exp\left(-c_2/\lambda T\right) \frac{1}{1-\exp\left(-c_2/\lambda T\right)}$$

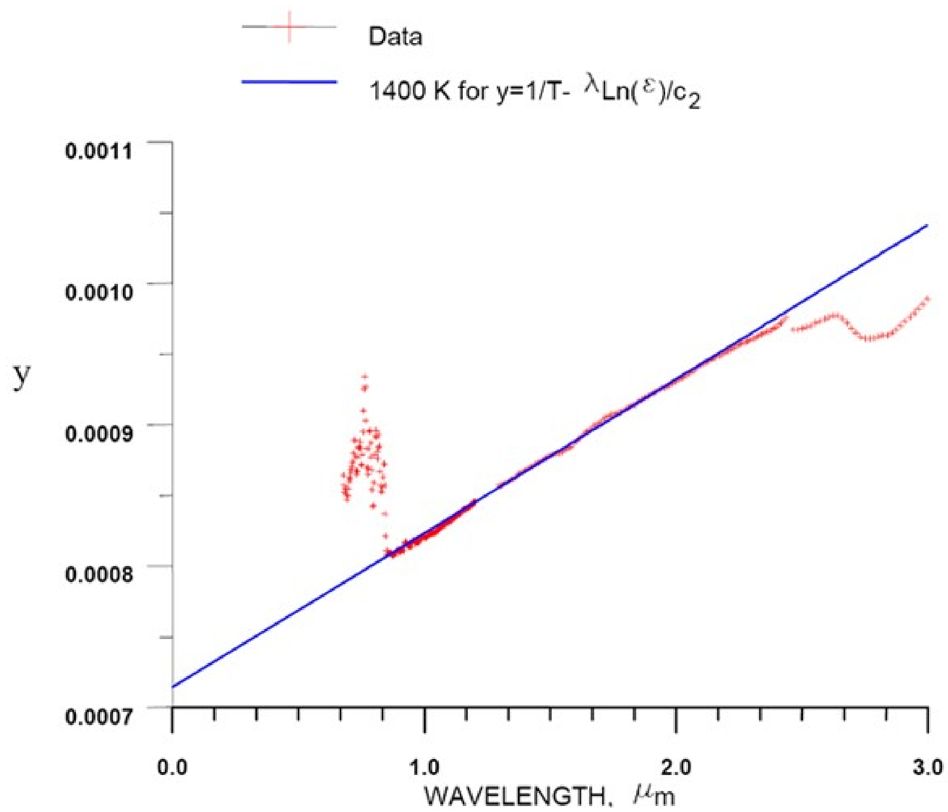
- Rewrite in form of *y=mx+b*:

$$\underbrace{\left(\frac{\ln\left(\frac{c_1}{\lambda^5} \frac{1}{L_\lambda} \right)}{c_2/\lambda} \right)}_{y} - \underbrace{\cancel{\left(\frac{\ln\left(1-\exp\left(\frac{c_2}{\lambda T} \right) \right)}{c_2/\lambda} \right)}}_{\approx 0} = \underbrace{\frac{1}{T}}_{b} - \underbrace{\frac{\lambda}{c_2} \ln\left(\varepsilon_\lambda \tau_\lambda\right)}_{mx}$$

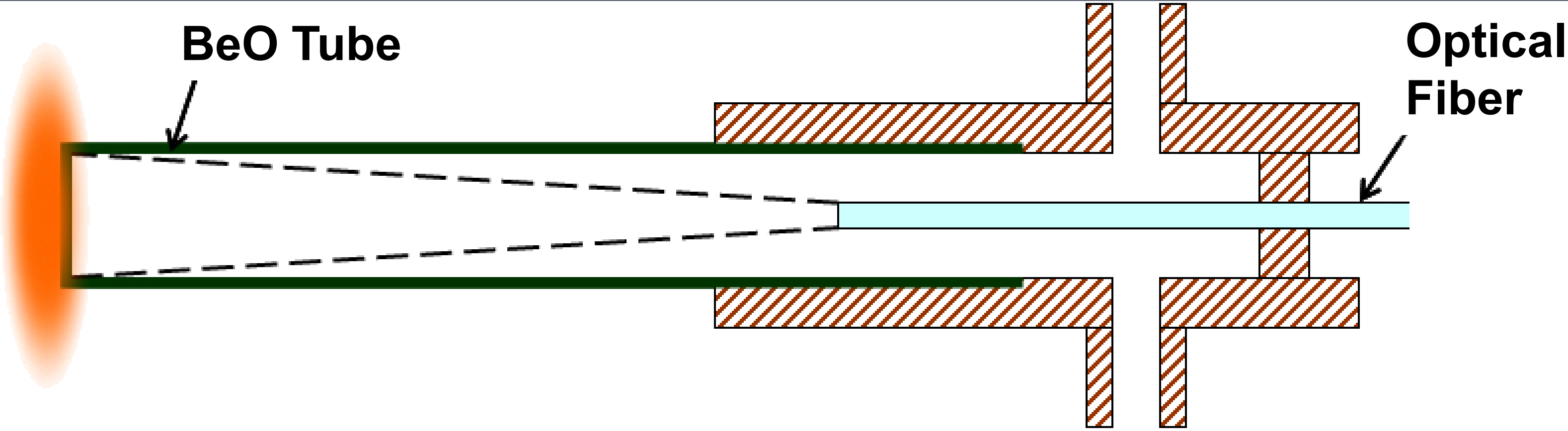
High Temperature Gas Temperature Probe

- Zirconia TBC Surface Measurement





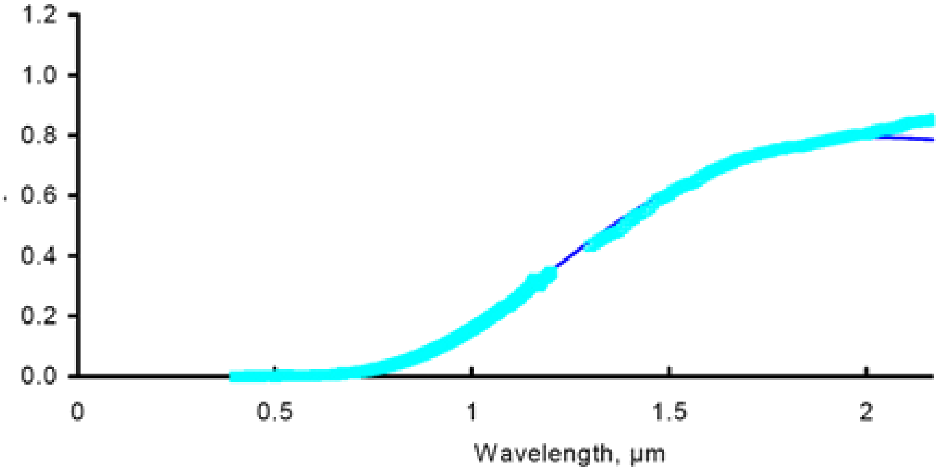
High Temperature Gas Temperature Probe

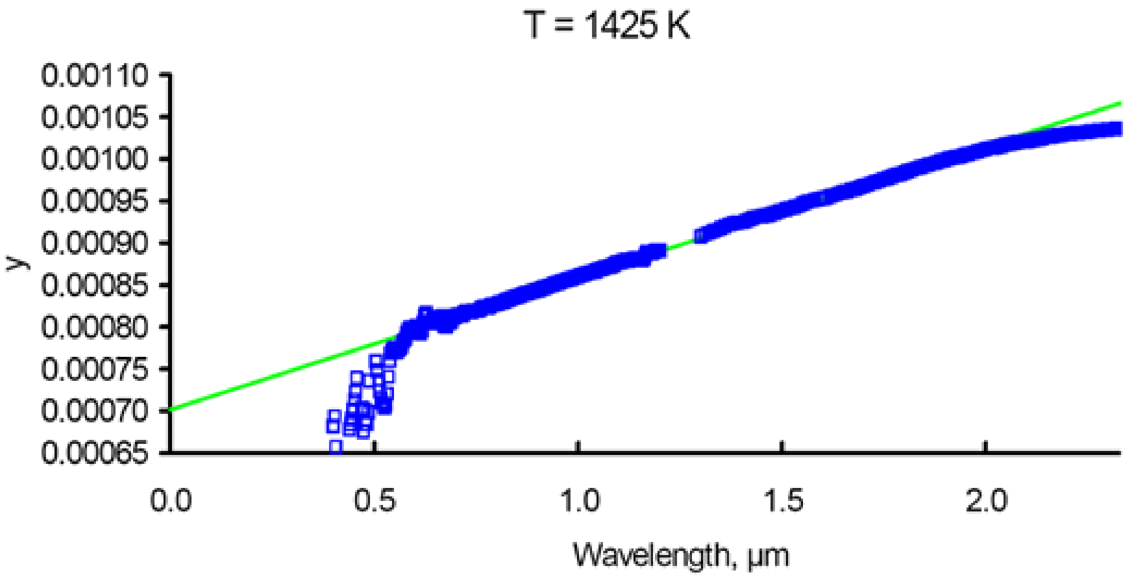


- Ceramic temperature probe sheath/support assembly

High Temperature Gas Temperature Probe

- Beryllia Gas Probe Tube Surface Measurement





High Temperature Gas Temperature Probe

With

- constant material properties
- no radiation correction

Gas and probe temperatures are related by

$$T_g = \frac{T(L)\cosh(aL) - T_b}{\cosh(aL) - 1}$$

where

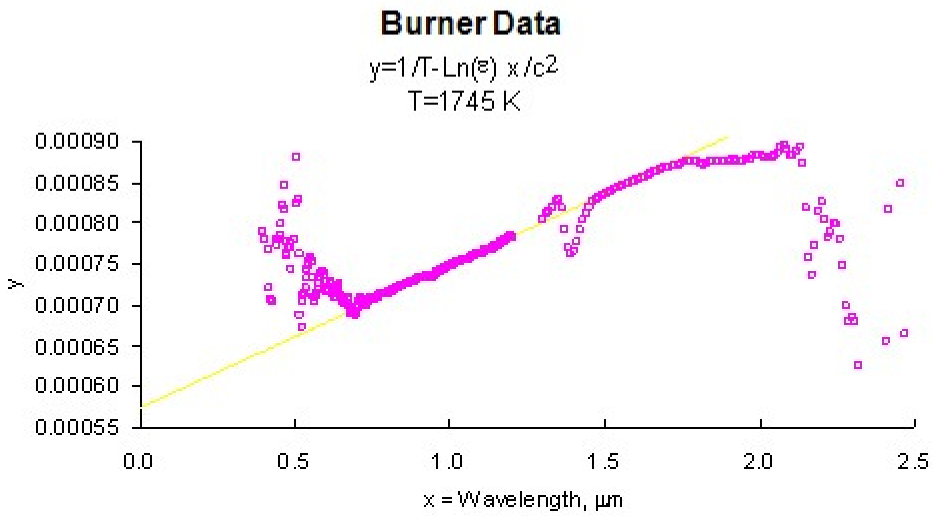
T_g = gas temperature

L = length of probe

$T(L)$ = temperature of probe tip

T_b = temperature of base of probe

a = f(h,k,D,t)



High Temperature Gas Temperature Probe

Conclusion

- Multiwavelength pyrometer can measure the temperature of a ceramic material without needing its emissivity.
- A gas temperature probe based on multiwavelength pyrometry is practical.

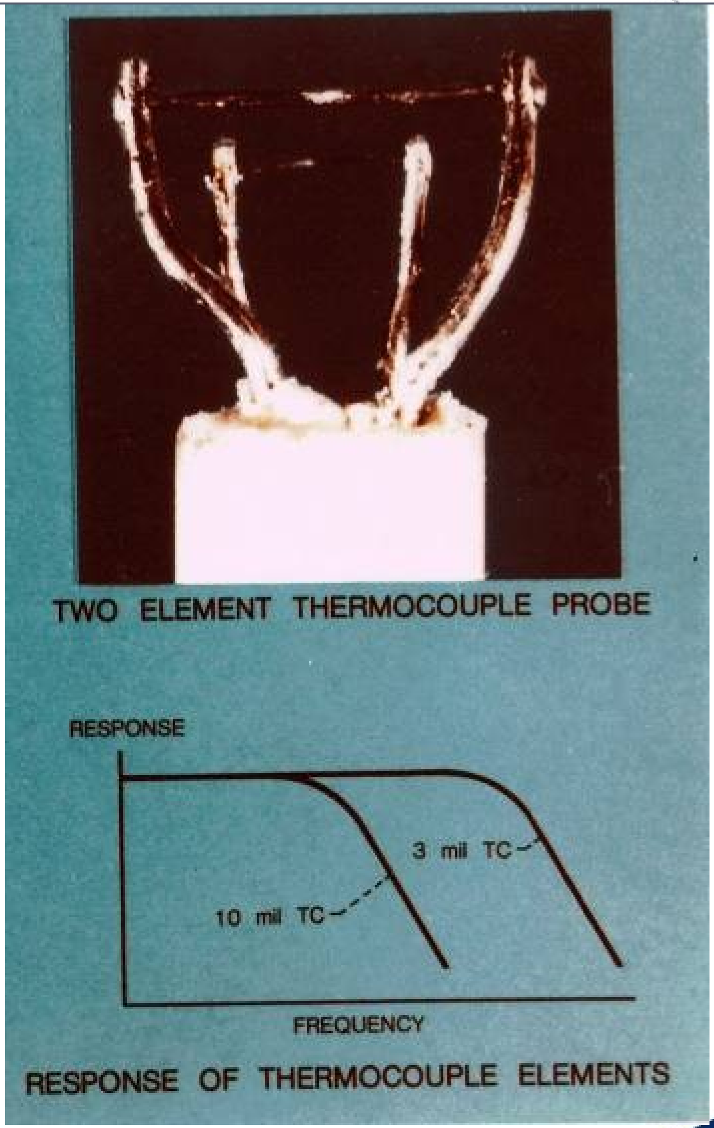
Future Work

- Redesign probe to be modular.
- Change shape of tip of ceramic tube to reduce thermal stress concentration.
- Use another fiber to increase signal level.
- Improve mathematical model of probe.

Dynamic Gas Temperature Measurement

Goal:

- Measure Gas Temperature Fluctuations in Turbine Engines
- T_{peak} = 3000°F
- $T_{dynamic}$ ±900°F
- Frequency to 1000 Hz
- Pressure to 20 atm
- Spatial Resolution < 0.2 in.
- Sensor Life – 5 hr minimum

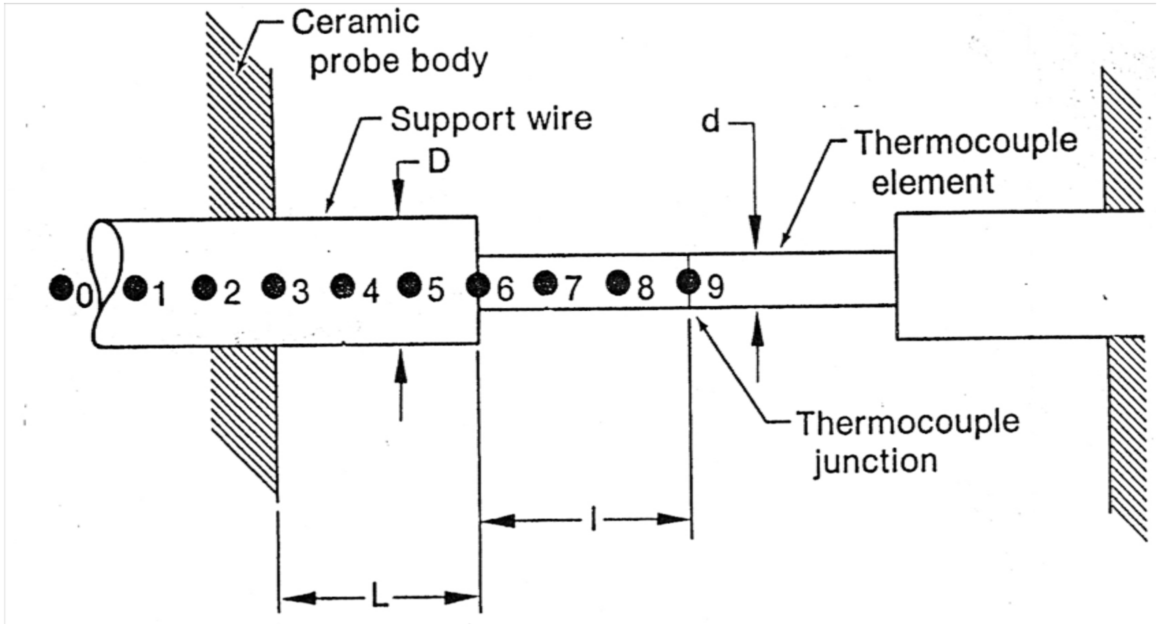


Dynamic Gas Temperature Measurement

- Must Solve

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} + \frac{4h}{\rho c D}\left(T_g(t) - T\right)$$

- Nine-node Finite Difference Model:



Dynamic Gas Temperature Measurement Compensation Process

- 1. The thermocouples are mathematically modeled as linear systems, whose transfer functions depend on *h*, the heat transfer coefficient.

- 2. The transfer function amplitude ratio for the two thermocouples is calculated for various values of *h*.

- 3. Data from the two thermocouples provides the *measured* value of this ratio.

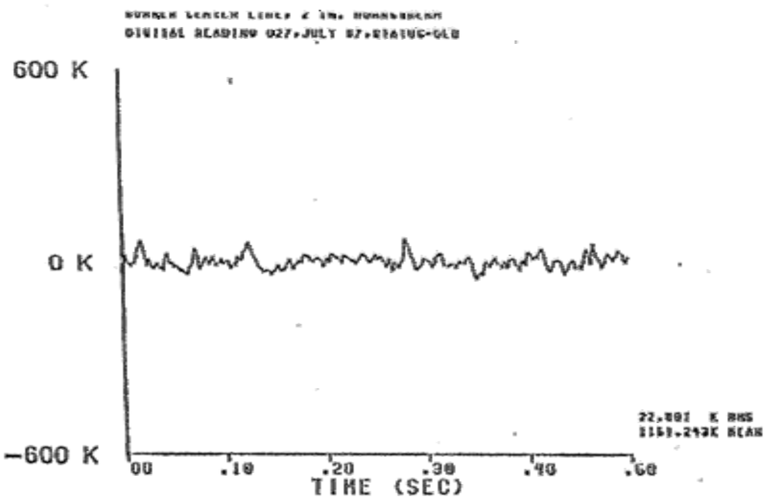
- 4. The measured value is compared with the various calculated values to find the best estimate of the in situ value of *h*.

- 5. Calculate the frequency compensation using this known value of *h*.

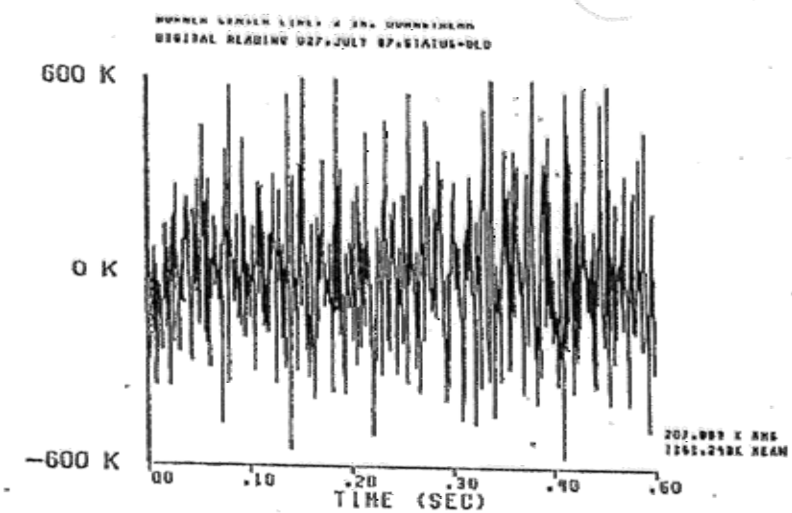
- 6. Full details are given in NASA TM 106119.

Dynamic Gas Temperature Measurement

- Test Results



UNCOMPENSATED

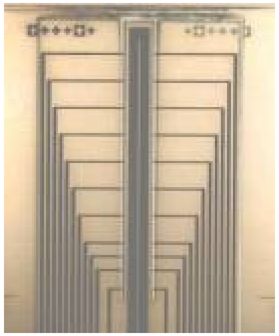


COMPENSATED

Thin Film Physical Sensors for High Temperature Applications

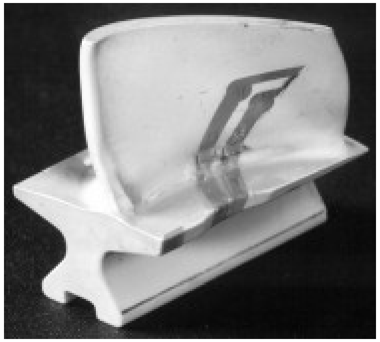
Advantages for temperature, strain, heat flux, flow & pressure measurements:

- Negligible mass & minimally intrusive (microns thick)
- Applicable to a variety of materials including ceramics
- Minimal structural disturbance (minimal machining)
- Intimate sensor to substrate contact & accurate placement
- High durability compared to exposed wire sensors
- Capable for operation to very high temperatures (>1000°C)

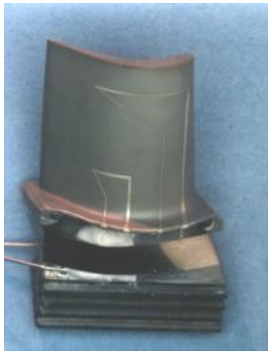


Flow sensor made of high temperature materials

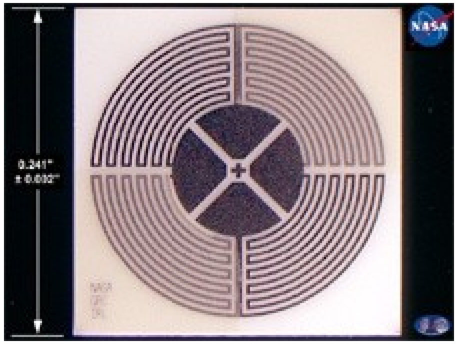
Multifunctional smart sensors being developed



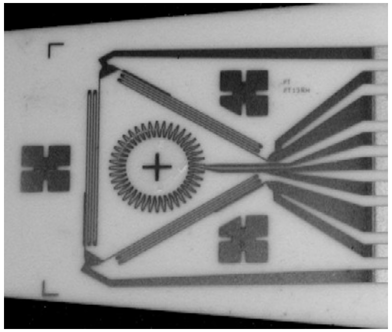
PdCr strain sensor to T=1000°C



Pt- Pt/Rh temperature sensor to T=1200°C



Heat Flux Sensor Array to T=1000°C



Multifunctional Sensor Array

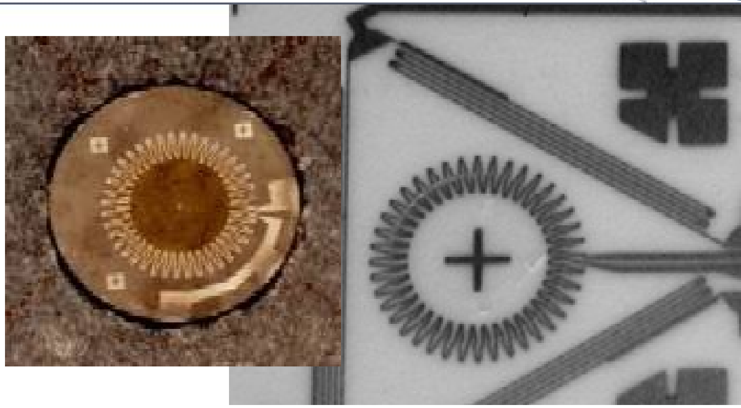
Heat Flux Sensors

Thermopile-type Heat Flux Sensor

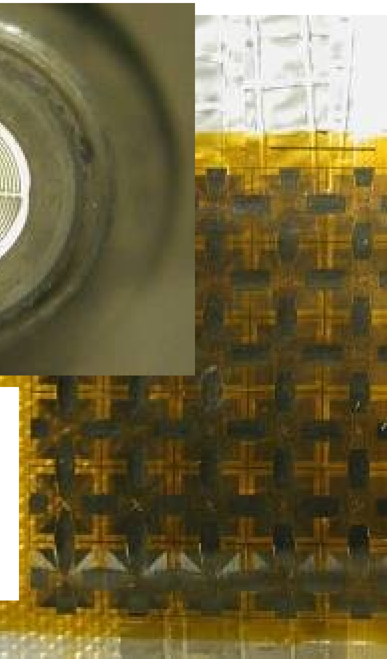
- Temperature difference across a thickness of insulation is measured by thin film thermocouples
- Insulation is a thin film TBC
- Sensitivity is increased by adding many thermocouple pairs in series to form a thermopile

RTD-based Heat Flux Sensor

- Temperature difference across a thicknesses of insulation is measured by thin film RTD’s
- Insulation may be a thin film TBC or the substrate itself
- Utilizing a Wheatstone bridge, this sensor is easier to fabricate and has a larger signal than thermopile-type



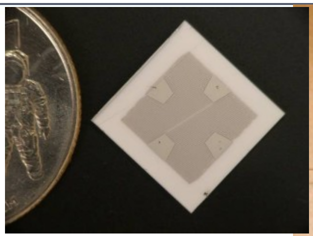
Thermopile Heat Flux Sensor on a plug (left) and as part of a Multifunctional Sensor (right)

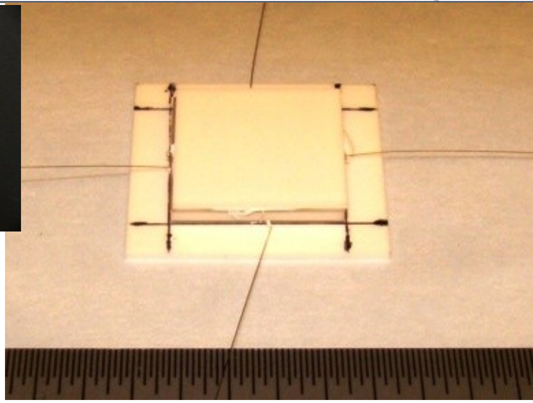


One-sided RTD Heat Flux Sensor (above); Double-Sided on Kapton (right)

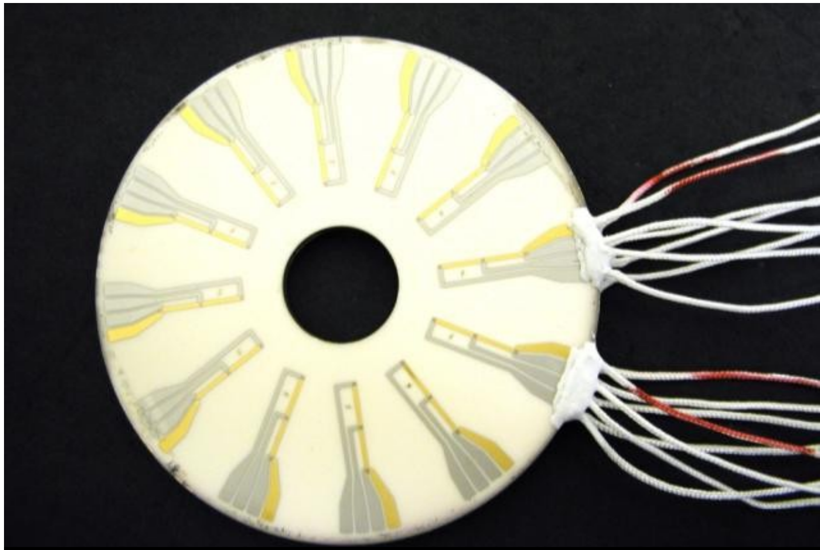
Metallic Thin Film
Heat Flux Sensor Applications

- High Temperature Heat Flux Sensors packaged and delivered to GRC Seals Group for **CEV/TPS Heat Shield Interface Seal Studies** at ARC
- High Temperature Au-Pt Heat Flux Sensors fabricated and delivered to **GRC Advanced Stirling Development Group** for direct measurement of thermal to electrical conversion efficiency in ASC Units
- Examining laser micro-machining as alternative to photolithography for lift-off sensor fabrication on rough surfaces such as CMCs as part of **NASA Fundamental Aeronautics - Supersonics Project**

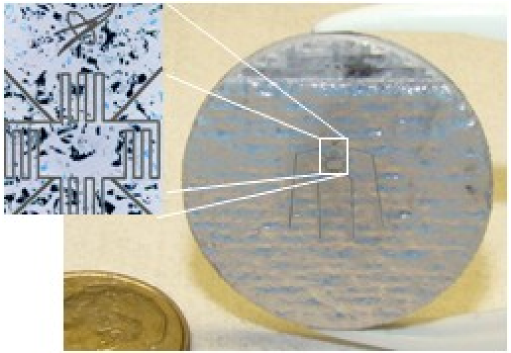




Delivered High Temperature Heat Flux Sensor for CEV/TPS (above); as packaged (left)



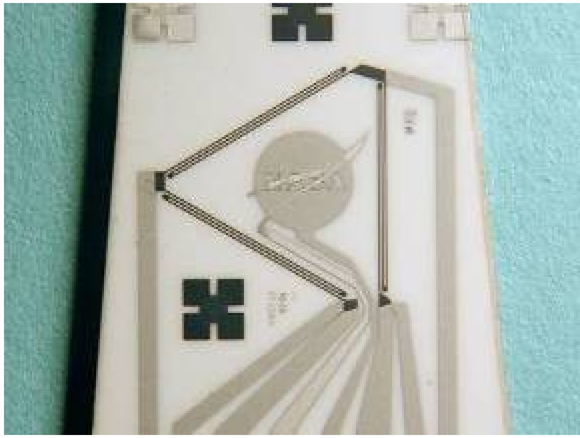
6.66 cm dia. Thin Film AuPt Heat Flux Sensor for Advanced Stirling Convertor Demonstration



RTD Heat Flux Sensor pattern micro-machined with a Nd:YAG laser on EBC-CMC in a sacrificial metal film

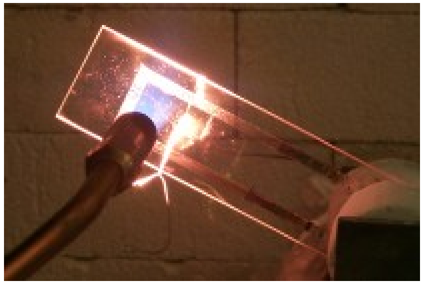
Novel Thin Film Sensor Technology Development

- Development of Thin Film Sensors with Ceramic, Laminate and Nanostructured Materials
  - Improve techniques for applying high temperature sensors onto complex structures
  - Develop thin film sensors to measure temperature, strain, and heat flux for hot section components
- Technology Challenge: Survivability in Extremely High Temperature Environments (>1500°C)
  - Build off of experience fabricating devices on more conventional components
  - Leverage partnerships with University of Rhode Island and NASA GRC Ceramics Branch for ceramic-based materials



Multilayered Ceramic Sensor with Minimal Apparent Strain Sensitivity

Ceramic TC Sputtering Targets fabricated by the NASA GRC Ceramics Branch



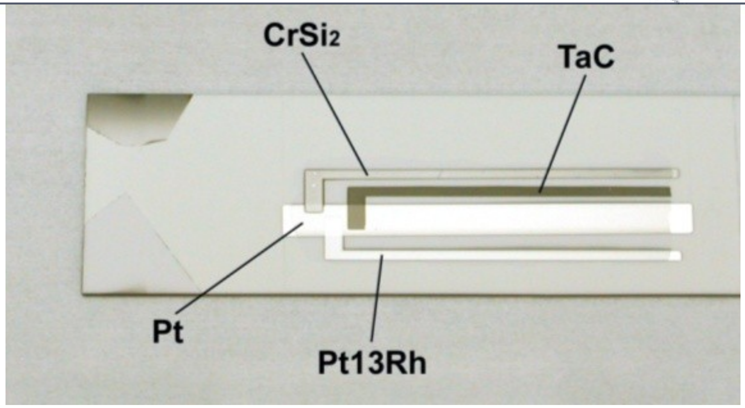
Ceramic Thermocouple fabricated at University of Rhode Island

RTD on Fan Blade

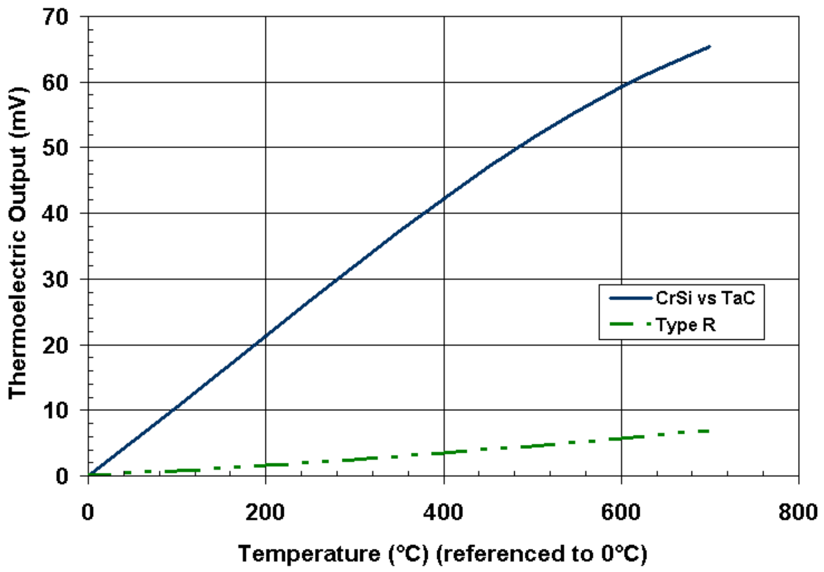
Sputtering System for Thin Film Sensor Fabrication

Considerations for Ceramic Thermocouples

- Silicides and Carbides have highest thermoelectric output of non-metallic thermocouple (TC) elements as bulk materials
- Carbides have a very high use temperature in inert and reducing atmospheres (>>3000°C)
- Most Robust Carbides: TaC, HfC, and ZrC
- Silicides form a natural passivation layer in oxygen
- High Performance Silicides: $CrSi_2$ and $TaSi_2$

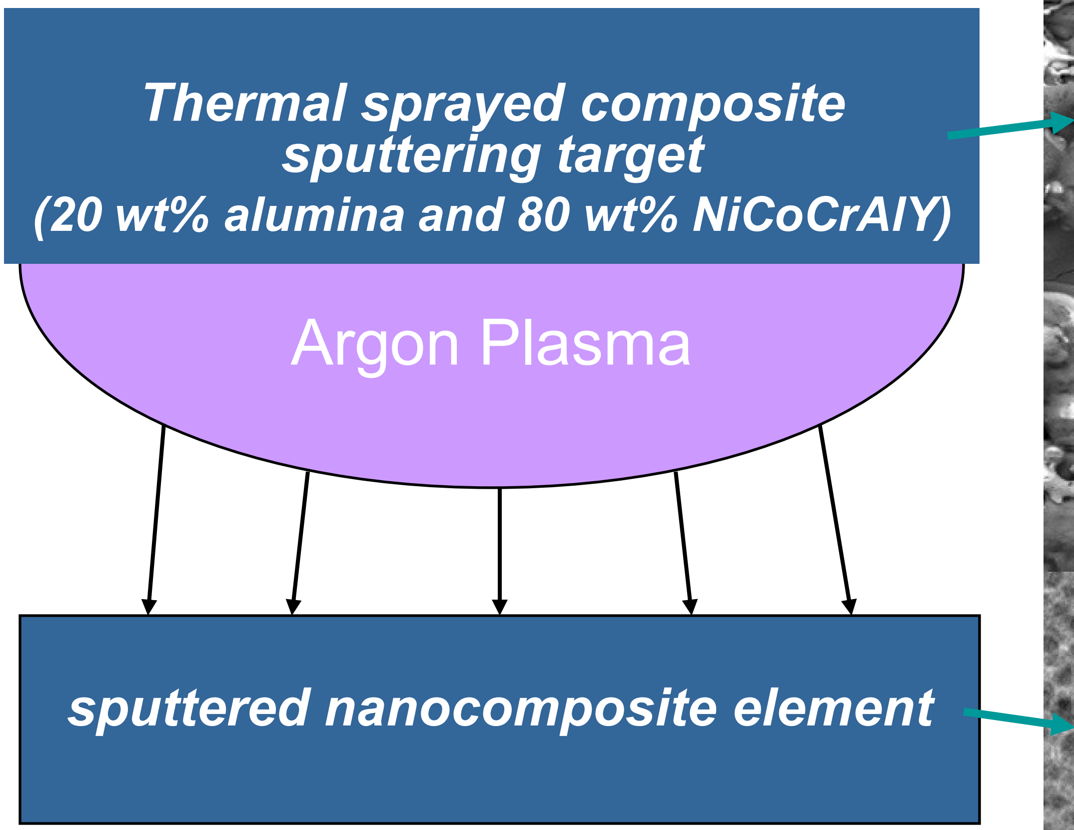


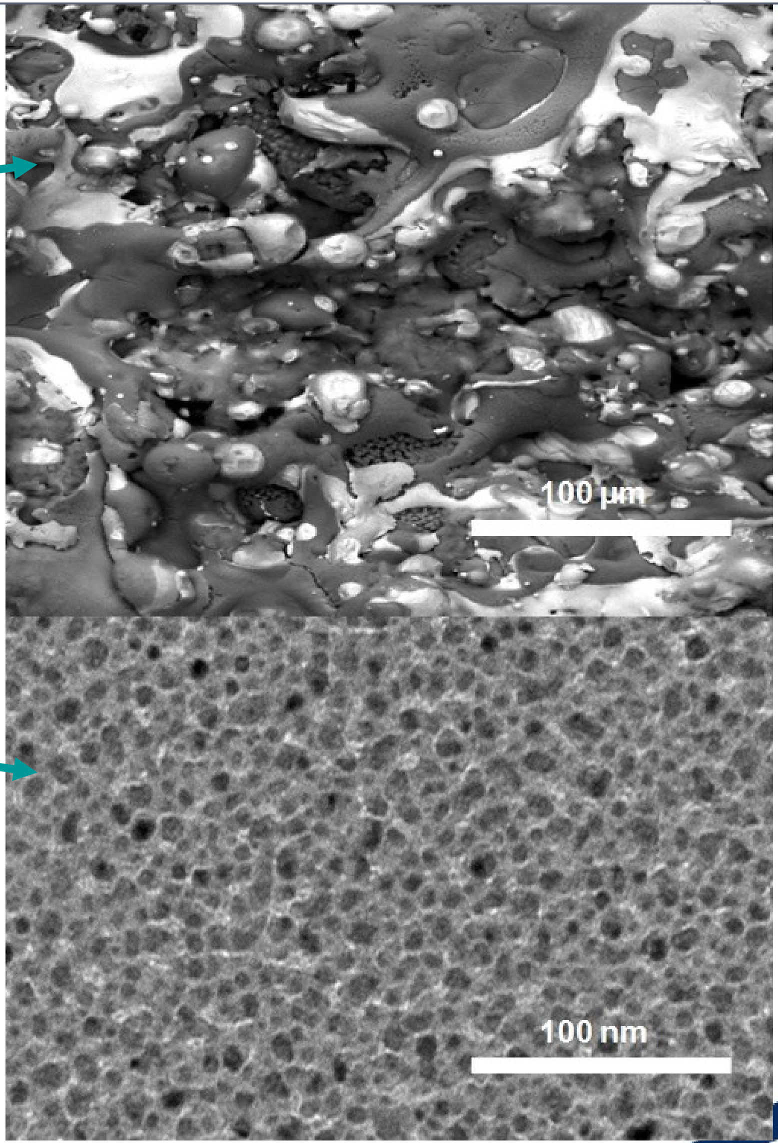
- **Thin Film Ceramic TC Sample and measured performance**



Sensors and Surface Technology Partnership

Fabrication of Nanocomposite Thermoelement





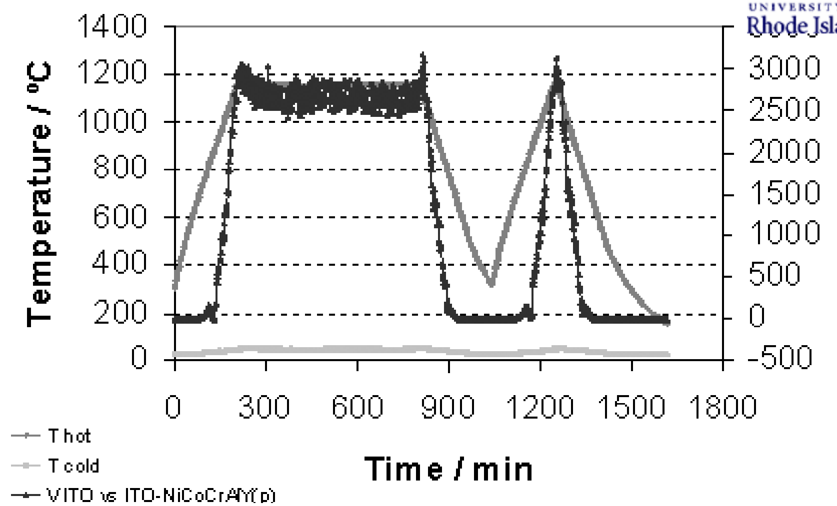
SEM micrograph of a thermally sprayed composite sputtering target (top) consisting of NiCoCrAlY and alumina phases and TEM of resulting nanocomposite (bottom). Note the dark phase is alumina and the light phase is NiCoCrAlY in the upper micrograph and this is reversed in the lower micrograph.

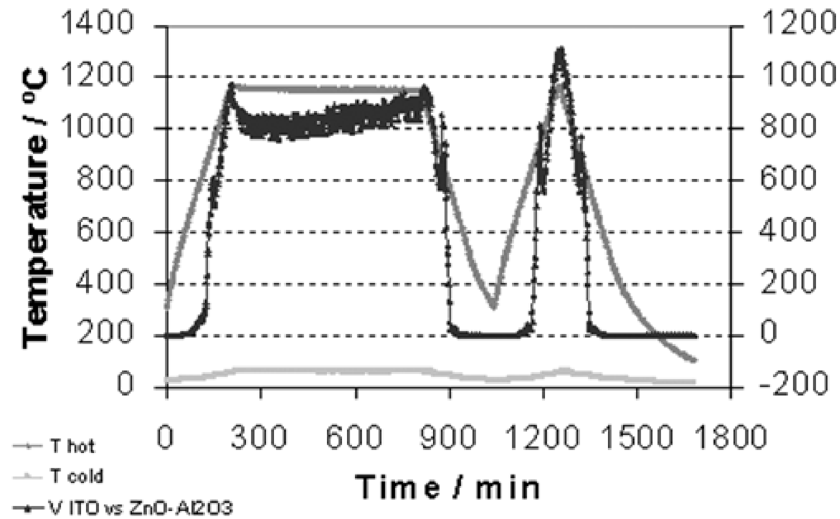
PIWG Propulsion Instrumentation Working Group

Nanocomposite Thermoelement Response

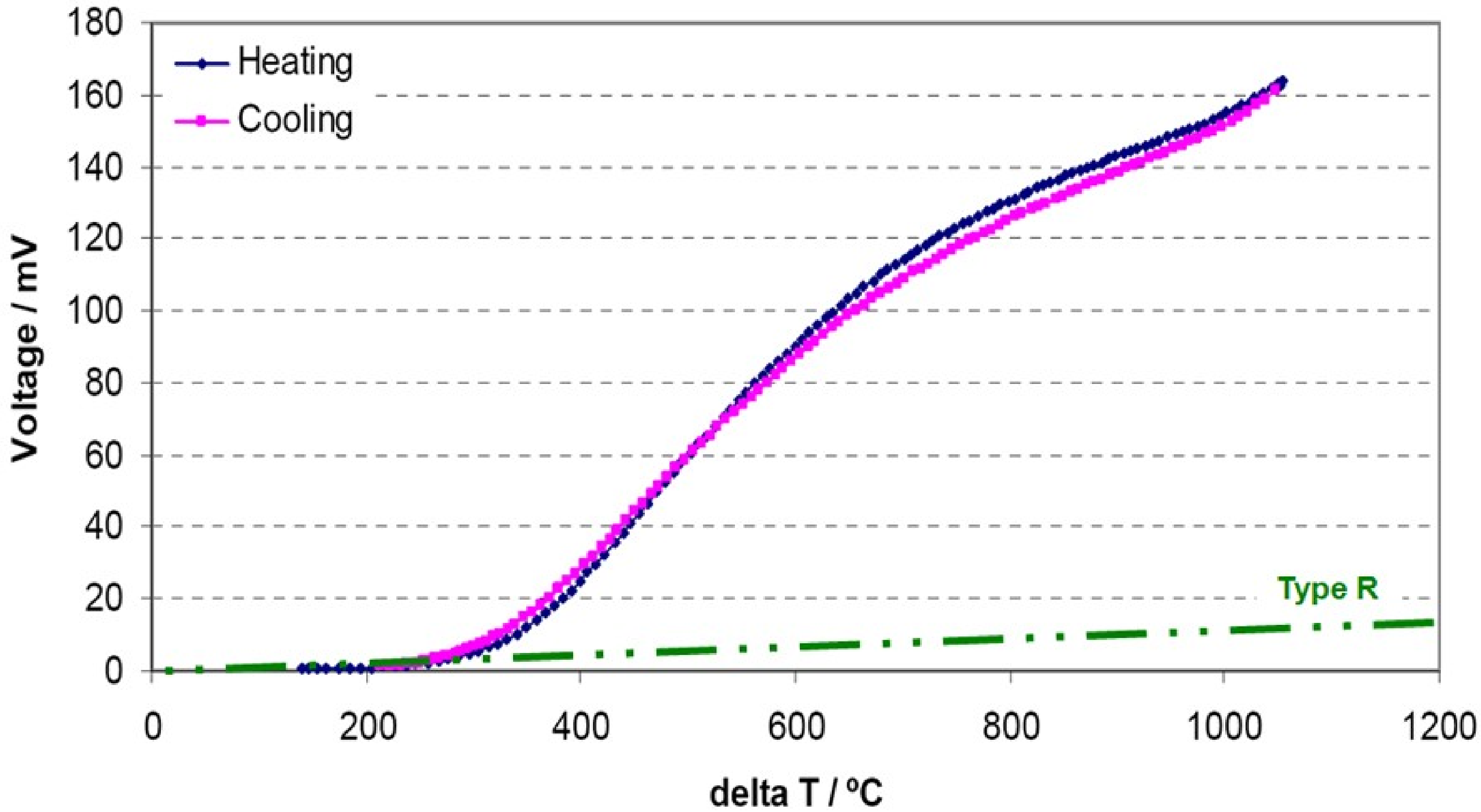
Sensors and Surface Technology Partnership

- The goal of this study is to develop a responsive ceramic thin film thermocouple for high temperature gas turbine engine applications.
  - Thin film thermocouples deposited directly on the blades and vanes are ideally suited for measuring the surface temperature of engine components during operation due to their small thermal mass.
  - Preliminary calculations indicate that enough electrical energy can be generated from the large thermal gradients that exist within a gas turbine engine to power active wireless devices as well.
- Thermoelectric properties of an ITO/ nanocomposite (NiCoCrAlY and alumina) bi-ceramic junction as a function of sputtering parameters is undergoing systematic investigation.
  - The emf/temperature behavior is dependent on the oxygen and nitrogen partial pressures in the plasma that controls the charge carrier concentration and stability of the bi-ceramic junctions.
  - The oxygen-doped ITO/nanocomposite thermocouple exhibits a very large maximum emf and Seebeck coefficient but also exhibits a large hysteresis upon heating vs. cooling.



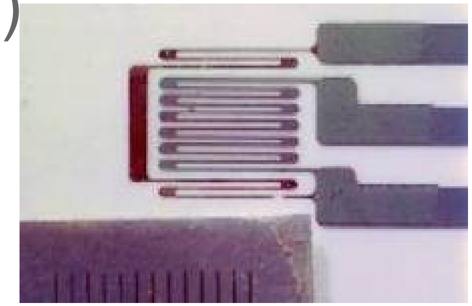


Thermoelectric EMF of Nanocomposite Film vs. ITO

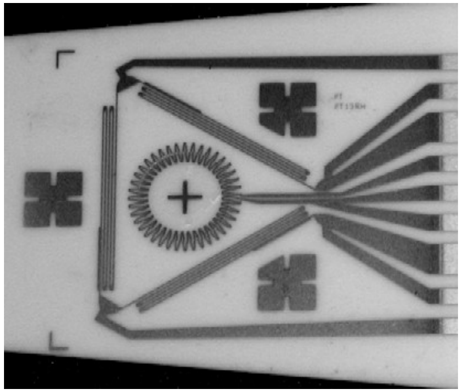


Considerations for Static Strain Gauges

- Required accuracy: ±200 με (±10% full scale)
  - Currently accomplished with a temperature compensating bridge circuit with PdCr
- Multifunctional Sensor design does not lend itself to compensating bridges
  - Multiple strain gauges in a rosette pattern does not allow compensation to be included in design
  - Design eliminates temperature effects if apparent strain is low enough
- High Temperature Static Strain measurements with Multifunctional Sensor requires a more passive method of <u>reducing or eliminating apparent strain</u>
- Temperature Sensitivity Goal for Multifunctional Sensor algorithm: <±20 με/°C



PdCr Strain Gauge in Compensation Bridge



Multifunctional Sensor Design

Apparent Strain

- Gauge factor (γ) of the strain gauge relates the sensitivity of the gauge to Strain (ε):

$$\frac{\delta R}{R} = \gamma \frac{\delta l}{l} = \gamma \varepsilon$$

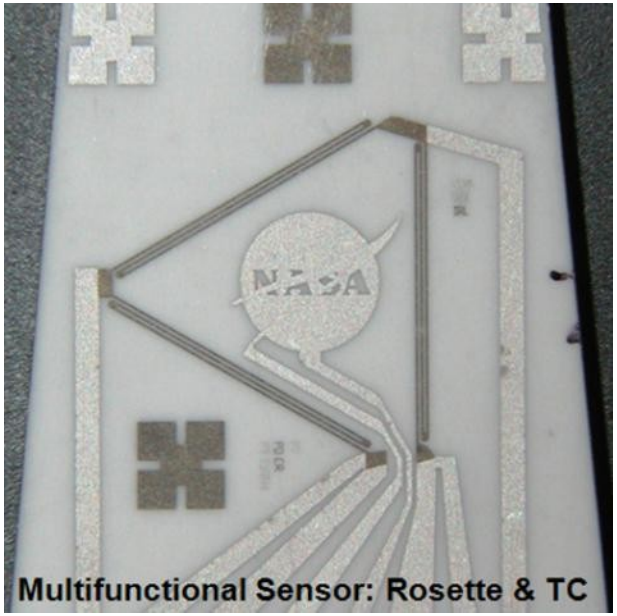
- Apparent Strain (ε_a) can be falsely interpreted as actual strain due to the gauge's Temperature Coefficient of Resistance (TCR) and Coefficient of Thermal Expansion (CTE):

$$\frac{\varepsilon_a}{\Delta T} = \frac{TCR}{\gamma} + \Delta CTE$$

- Goal: To minimize apparent strain by minimizing TCR and maximizing gauge factor

Multilayered Multifunctional Sensor

- TaN layered to PdCr strain gauge for the passive elimination of apparent strain sensitivity
- Initial test to 150°C
  - Gauge Factor: 1.2
  - Resistivity: 146 μΩ-cm
  - TCR: +15 ppm/°C
  - $\varepsilon_a/\Delta T$: +12 με/°C (<20με/°C)
- Follow-up test to 600°C
- Potential Issues
  - Multilayer Delamination / Diffusion
  - Compatible with sacrificial lift-off patterning process (Reactivity)
  - High Temperature Expansion Issues (CTE)
- Other Materials?



Multifunctional Sensor: Rosette & TC

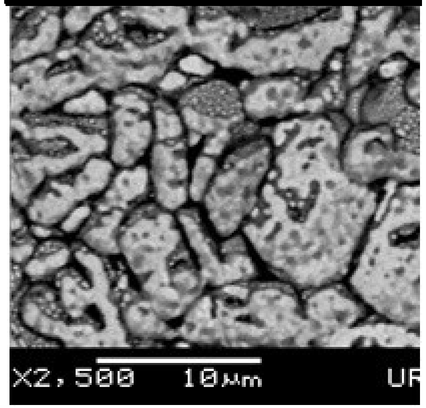

GRC Thin Film Lab

ITO-Nanocomposite Thin Film Strain Gauges

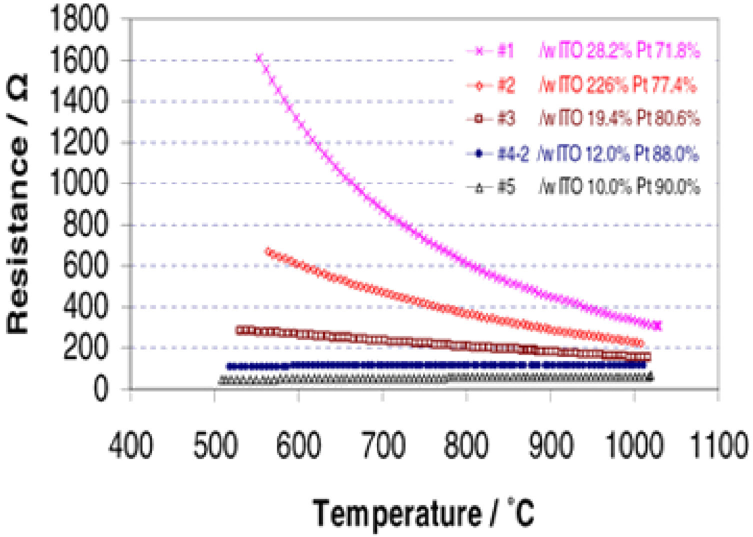
Sensors and Surface Technology Partnership

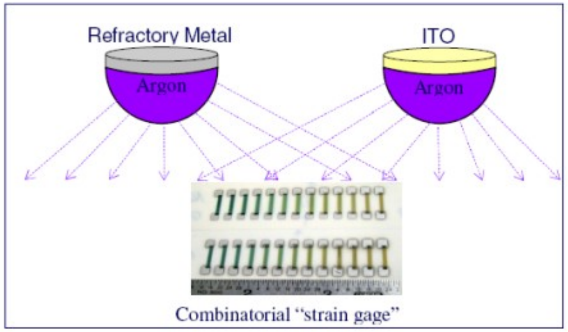
- Low TCR nanocomposite strain gauges fabricated by co-sputtering Indium-Tin Oxide (ITO) and refractory metals
- The TCR's measured for several ITO-Pt mixtures via Combinatorial Library
- Candidate Sample Result:
  - Gauge Factor: -26
  - TCR: -50 ppm/°C
  - $\varepsilon_a/\Delta T$: +2 με/°C (< 20 με/°C)
- Physics not understood at this time; more studies on-going

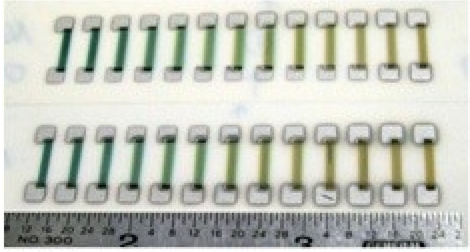
Backscattered SEM image



Equal Volumes of Pt and ITO → Min. TCR







Combinatorial Strain Gauge Library

Summary

- For the advanced engines in the future, knowledge of the physical parameters of the engine and components is necessary on the test stand and in flight
- NASA GRC is leveraging expertise in thin films and high temperature materials to measure hot section gas and surface temperature, heat flux and static and dynamic strain
- Investigating the applications of thin film ceramic sensors as replacement for noble metals
- Currently optimizing deposition of candidate materials
- Research support provided by:
  - Aviation Safety Program of NASA's Aeronautics Research Mission Directorate through the Aircraft Aging and Durability Project
  - Fundamental Aeronautics Program of NASA's Aeronautics Research Mission Directorate through the Supersonics Project

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- Kimala Laster
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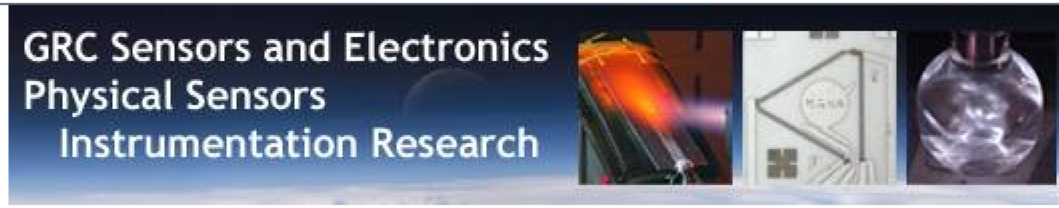
Contacts



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http://www.grc.nasa.gov/WWW/sensors/PhySen/

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